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Efficacy of Directional Cues from a Tactile System for Target Orientation during Helicopter Extractions over Moving Targets

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14. ABSTRACT
Military and civilian helicopters have been extracting downed and injured personnel for decades. Stabilizing the aircraft in a hover position in areas of limited contrast is a difficult task made more complex when over water due to the motion of the waves and the drift of the rescue target. This study assessed the efficacy of a tactile system providing directional cues in a simulated extraction task under varied conditions (e.g., degraded visual environment, fatigue). The results support the use of cues delivered by a tactile system. Results also indicated that participants were in fact fatigued (evidenced by mood and vigilance data) but performance was unaffected by this condition. The data patterns indicate that participants developed a strategy for using the cues (in some cases with minimal training), which influenced how well they performed.

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Introduction

Military and civilian helicopters have been used for extracting downed and injured personnel since the Korean War. Rescue hoist flight operations are flight tasks required of many helicopter pilots. It is common knowledge among helicopter pilots that maintaining a stabilized hover position during rescue hoist operations in areas of limited contrast (over water, desert, and snow) is a difficult task. When over water, the task is further complicated by the motion of the waves and the drifting (due to water currents and helicopter rotor downwash) of the person(s) to be rescued. Maintaining a hover over the victims requires constant control adjustments of the helicopter by the pilot. Currently, such control adjustments are made based on the pilot's very limited ability to view below the aircraft and the verbal instructions of a non-flying crewmember. The time between relaying, receiving, and acting on verbal instructions hampers extraction attempts and causes critical delays in overwater rescues. Any method that may speed the extraction process may result in quicker medical care for persons with potentially life-threatening conditions (e.g., injuries, hypothermia, drowning). This study assessed the ability of a tactile cueing system to provide to the pilot nonverbal, tactile directional cues as to a dynamic target's position. The results of this study have the potential to validate the use of sensor technology for navigation and spatial orientation when vision is degraded or not available.

Background

The tactile situation awareness system (TSAS) was developed to provide information via the under-utilized sense of touch (Rupert, Guedry, & Reschke, 1993; McGrath, Estrada, Braithwaite, Raj, & Rupert, 2004; McGrath, Suri, Carff, Raj, & Rupert, 1998). Providing tactile information allows the pilot to maintain orientation while looking away from the aircraft instrument panel. The full TSAS array consists of a custom fit, upper-body torso suit, shoulder straps, and a seat. All three components contain tactile stimulators (tactors) that respond to hardware and software in the aircraft and provide information to the pilot on the aircraft's altitude, drift direction, and magnitude.

One major disadvantage to the full TSAS array is the impracticality of its implementation in military settings. Specifically, the system is bulky, expensive, and difficult to maintain, and therefore not a realistic option in the harsh field environments in which Army Aviation operates. While research flights for the TSAS conducted in a UH-60 helicopter resulted in improved aircraft control, increased pilot situational awareness, and reduced pilot workload (McGrath, et al., 2004; Raj, Suri, Braithwaite, & Rupert, 1998), the expense of fitting each pilot with a custom TSAS vest remains a challenge.

Given the potential of the TSAS, efforts were made to construct and develop a more practical Army system. Thus, TSAS-Lite, which consists of eight tactors placed every 45 degrees around the waist in a belt, was developed. Curry, Estrada, Webb, and Erickson (2008) examined whether this modified system proves as effective as the full TSAS array in providing to the pilot helicopter drift information. The results showed that the limited-display provides increased aircraft control and safety during low speed maneuvers near the ground in degraded visual conditions. Even in fatigued pilots, following 31 hours of sleep deprivation, the TSAS-Lite

display augmented traditional aircraft instruments in an intuitive, non-visual manner, particularly with a hovering task. These results showed that the addition of TSAS-Lite significantly improves pilots' ability to control drift during take-off and reduces drift error during hover. In fatigued pilots, all measures of performance related to drift were improved with use of the belt compared to performance without the belt. Overall, the results indicated that the belt significantly improves pilot perception of drift and situation awareness, and reduces mental stress.

To further evaluate the effectiveness of TSAS-Lite during varied maneuvers and under a range of conditions, the present study examined the efficacy of TSAS-Lite belt specifically for target orientation in helicopter extractions over moving targets (a more difficult task than maintaining hover over stabilized targets). We hypothesized pilots would be more efficient at maintaining their position over a moving target when equipped versus not equipped with the TSAS-Lite belt.

Method

The protocol was reviewed and approved by the U.S. Army Medical Research and Materiel Command Institutional Review Board (USAMRMC IRB) prior to implementation. To test the above stated hypothesis, this study employed a mixed-model 2^4 factorial design. There was one between-subjects variable, *training amount* (minimal, additional), and three within-subjects variables, *state* (rested, fatigued), *visual environment* (clear, degraded), and *TSAS-Lite belt* (active, inactive). The study was conducted at the U.S. Army Aeromedical Research Laboratory (USAARL) and utilized the laboratory's UH-60 flight simulator.

Participants

Sixteen UH-60 rated healthy aviators participated in the study. The mean age was 33 years (SD = 8.65), 14 were male, 13 were U.S. Army Active-Duty, 1 U.S. Army National Guard, 1 U.S. Army Reserve, and 1 U.S. Army component unreported. All participants were medically screened for a recent history of seizures, history of incapacitating simulator sickness, current use of medications that alter sleep/wake cycles, current acute illness, and significant sleep deprivation 2 days prior to participation.

Materials

Fatigue.

Measures indicative of fatigue level were included to confirm fatigued versus rested states. Administered were two assessments of subjective mood state and alertness; the Profile of Mood States (POMS), a 65-item adjective checklist with a Likert response scale (McNair, Lorr, & Droppleman, 1992), and a visual analogue scale (VAS) response format (Penetar et al., 1993). The POMS questionnaire yields six sub-scale scores: tension-anxiety, depression-dejection, anger-hostility, vigor-activity, fatigue-inertia, and confusion-bewilderment. There are eight state (versus trait) adjectives measured by the VAS: alert, anxious, energetic, confident, irritable, jittery, sleepy, and talkative. Also, a 5-minute psychomotor vigilance task (PVT) was used to

measure alertness. The PVT was administered on a hand-held personal digital assessment. This device was validated at the Walter Reed Army Institute of Research and is displayed in figure 1 (Thorne, Johnson, Redmond, Sing, & Belenky, 2005). Data collected from the PVT included mean reaction time and number of lapses (responses over 500 milliseconds). Fatigue measures were administered pre-flight.

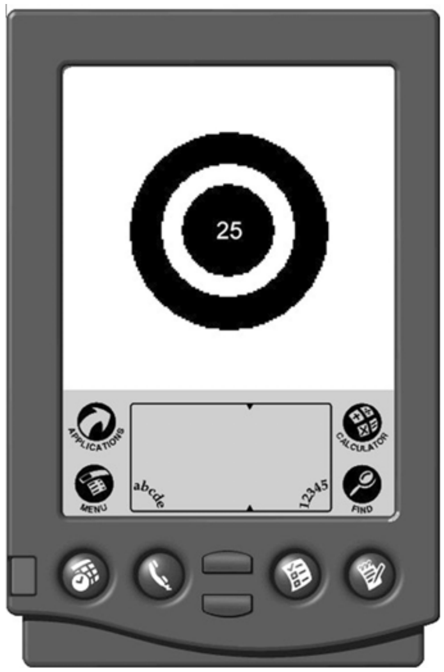

Figure 1. Hand-held PVT device (Thorne et al., 2005).

Workload and situational awareness (SA).

A post-flight questionnaire regarding workload and SA (visual analogue scale) and the China Lake Situation Awareness scale (CLSA; Adams, 1998) were administered to assess each pilot's perception of his/her own ability to control the aircraft based on his/her awareness of the aircraft status (e.g., attitude, airspeed, heading, geographic position). Also, an open-ended response format questionnaire regarding the TSAS belt was administered post-flight.

General health status.

For the purpose of monitoring general health status during the study, vital signs, including oral temperature, blood pressure, and pulse, were recorded using an IVAC Model 4200 VitalCheck. Vital signs data were not included in the statistical analysis.

Flight simulator.

The UH-60 research flight simulator consists of a simulator compartment containing a cockpit, instructor/operator station, an observer station, and a 6-degree of freedom motion

system (figure 2). It is equipped with six Dell precision 450 personal computer visual image generator systems that simulate natural helicopter environment surroundings for around-the-clock ambient light conditions. The research data acquisition system consists of a laptop computer that samples and stores up to 30 flight parameter variables. The key flight parameter dependent variable in this study was range (ft) of "helicopter" from target.

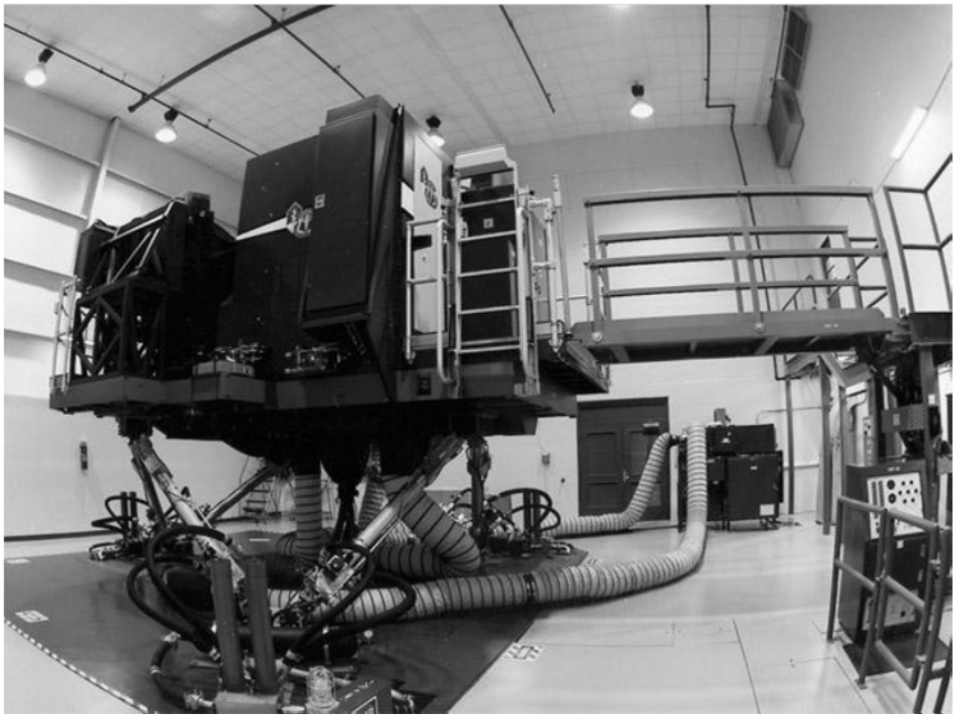

Figure 2. USAARL UH-60 flight simulator.

Tactile system.

The early experiments involving tactile cueing using pager motors were not successful in the aviation environment due to ambient noise and vibration obscuring the tactile stimulus (see McGrath, 1999 for a discussion). For the past 10 years the electromechanical tactors used for TSAS experiments manufactured by EAI have proven sufficiently robust to provide tactile cueing in the noisy helicopter environment. Recent technology developments in piezoelectric materials allow for much lighter, less obtrusive, variable frequency, tactile stimulators thus providing more opportunities for tactile information to augment current environments.

The TSAS-Lite belt consists of a customized eight channel tactor driver board, and eight electromechanical tactors (Engineering Acoustics, Inc.). The belt is made of a flexible neoprene with Velcro™ fastenings (figure 3). The aircraft seat also contains six tactors and two in the shoulder harness (one left, one right) to provide altitude information. The central processing unit and tactor drive electronics are protected in a water-resistant-sealed-housing with data, tactor, and operator switch interfaces. The system stimulates the tactile sense to relay to pilots information regarding spatial orientation and situational awareness. Specifically, the tactors

provide a vibrating stimulus at 90Hz +/- 20 percent with three rates of firing depending on pre-set flight conditions. The sensation provided to the pilot by the tactors is similar to the vibration of a standard electric toothbrush. Altitude, position, velocity, and vector information is transmitted from the UH-60 flight simulator to the tactile system. This information is displayed via the electromagnetic tactors located on the belt. During flight maneuvering, the location of the tactor on the belt-line is used to indicate the direction of the target's motion (drift) relative to the pilot's position. This information determines whether and which tactor produces a stimulus and at what intensity. For example, when the helicopter (simulator) drifts to the left, the corresponding left position tactor vibrates to alert the pilot of the drift so that he/she can compensate by moving the helicopter to the right. Tactor data were recorded every 100 milliseconds (ms) with respect to the intensity of each tactor stimulus (0 = no stimulus, 1 = mild stimulus, 2 = moderate stimulus, 3 = strong stimulus). Each tactor was labeled by location: front left (FL), front (F), front right (FR), right (R), back right (BR), back (B), left back (LB) and left (L).

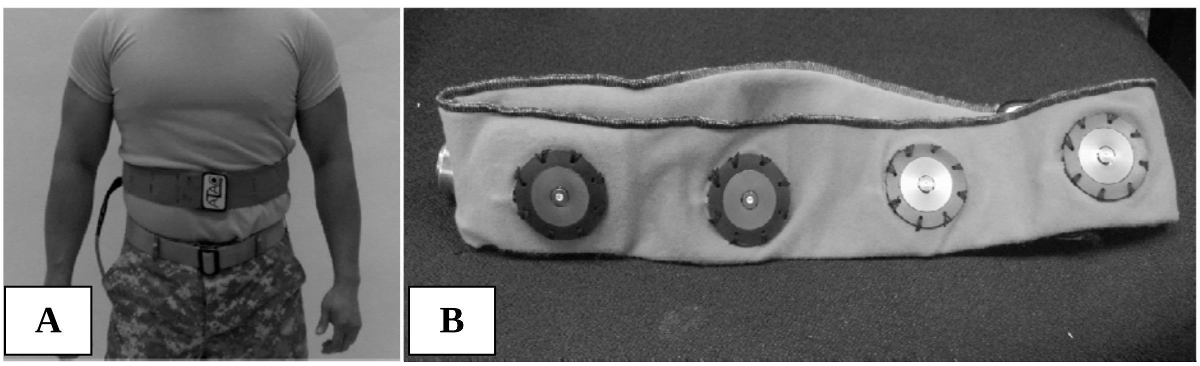

Figure 3. TSAS-Lite belt: (a) belt worn by aviator and (b) inside view of belt.

Procedure

Participants arrived at the laboratory at 0600 hours on Day 1 for in-processing including informed consent and medical screening. When schedules permitted, two participants completed the study simultaneously. Upon enrollment, participants trained in the UH-60 research flight simulator and Cobra TSAS demonstrator in the use and interpretation of the cues from a tactile garment and seat. This training consisted of one or more simulator sessions (each lasting 60 minutes) beginning on Day 1 (depending on whether the participant was assigned to the minimal or additional training group). Data collection flights consisted of simulated flying to a ship where the helicopter landing deck was used as the moving target (figure 4). In each flight, participants were to hover the helicopter over the moving target for approximately 10 minutes after which participants continued to hover for approximately 30 seconds while visually distracted. The order of the levels of the first within-subjects variable (state: rested and fatigued) could not be counterbalanced due to funding and practicality limitations. Thus, participants completed rested conditions on Day 1 and fatigued conditions on Day 2 (following one night of continuous wakefulness). Each day, each participant performed four, 10-minute stabilized hovering

maneuvers (at 70 feet above ground level) over the moving target under the four test conditions (TSAS active and good visual, TSAS active and degraded visual, TSAS inactive and good visual, TSAS inactive and degraded visual). A good visual environment was defined as clear with 7 miles visibility and a degraded visual environment as overcast with less than a quarter mile visibility. The order of these four flights were randomized (i.e., randomized without replacement) to avoid order effects while keeping the total numbers in each condition equivalent. The testing schedule is presented in table 1.

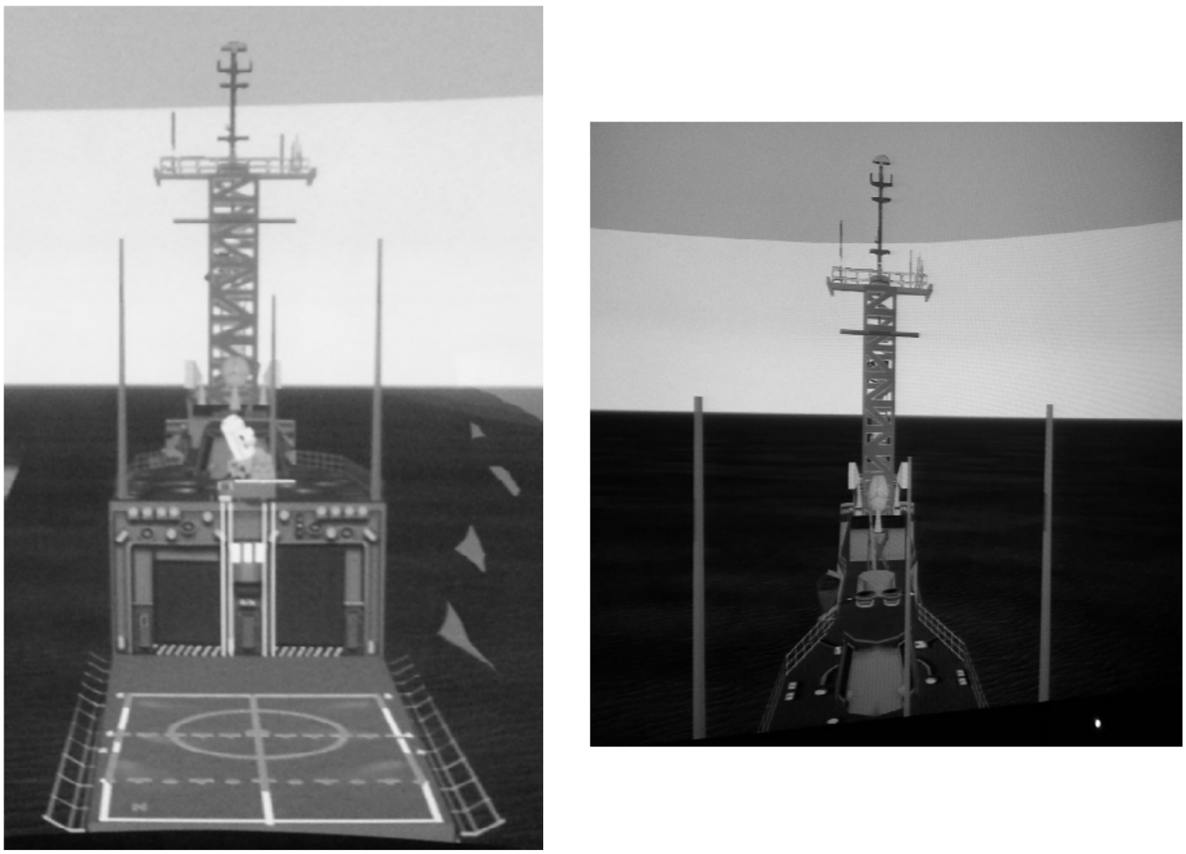

Figure 4. Visual display during hover maneuver task (*visual environment* - clear). Image on the left depicts a higher range from target than the image on the right.

Table 1.

Example of schedule of events. Times were subject to modification depending on whether two participants were engaged in the study subsequently.

Enrollment: 1) Informed Consent
2) Medical History
3) Medical Evaluation

Day 1		Day 2	
0630	Arrival	0300	Vital signs
0700	Vital signs	0700	Vital signs
0730	Simulator training UH-60	0730	TSAS training COBRA
0830	TSAS training COBRA simulator	0830	Recreation
0930	Recreation (video games, movies, etc.)		
1100	Vital signs/Lunch	1100	Vital signs/Lunch
1200	TSAS training in simulator	1200	TSAS training in simulator
1300	Recreation	1300	Recreation
1400	Flights (rested condition)	1400	Flights (fatigued condition)
1500	Vital signs	1500	Vital Signs
1515	Cognitive training/testing	1515	Cognitive training/testing
		1600	Exit exam
1630	Dinner	1630	Participant driven home
1900	Vital signs		
1915	Recreation; kept alert overnight		

Quality control and statistical analysis

Flight data

Flight data were sampled every 100 milliseconds (ms). The average length of each flight was 750.343 seconds (12.506 minutes) resulting in an average of 7503 rows of data per flight. With eight flights per participant, and a total of 16 participants, a total of 960,439 rows of data were recorded. During data collection, the research technician electronically recorded events such as the onset of the hovering maneuver and crashes to ease the task of partitioning the dataset and determining relevant rows of data. Due to the magnitude of data recorded, data from each flight were stored individually to minimize error during cleaning (removing irrelevant rows of data) the dataset. Data were stored in text files and converted to Microsoft® Excel 2010 files. Once prepared for analyses, files were converted back to text files. Aggregate means were calculated for each participant's flights and used in the analyses. Statistical outliers (3 standard deviations ± the mean) were identified, examined, and removed prior to aggregation. All analyses were then conducted using SPSS 19.0 and Minitab 16.

Questionnaire and PVT data

The majority of the questionnaires were administered electronically and the responses were recorded in text files. Data entry accuracy for the paper and pencil questionnaires was assessed using a 10 percent sample. The visual analogue post-flight scale data were analyzed using a repeated-measures multivariate analysis of variance (MANOVA) to assess the effects of *state*, *visual environment*, and *TSAS-Lite belt* on perceptions of workload and SA. The scoring of this scale required the measurement of the participants' tick mark from the left end of the line (in millimeters). The proportion of the line as indicated by the tick mark was then calculated. The CLSA data were analyzed using a repeated-measures ANOVA with *state* and *TSAS-Lite* as the independent measures. The subjective mood assessments were analyzed using repeated measures MANOVAs using *state* (levels: rested, fatigued) as the independent variable. Finally, the PVT mean reaction times and number of lapses (responses greater than 500 ms) were analyzed using paired-samples *t*-tests.

Analysis of flight and tactor data

Three main approaches were taken to analyze aspects of the flight data. First, a mixed-model ANOVA was used to evaluate the effects of *state*, *training amount*, *visual environment*, and *TSAS-Lite belt* on flight performance (range of helicopter from target) during the hover maneuver. Subsequent, independent-samples and paired-samples *t*-tests were used to determine differences between groups for any significant interaction effects. Second, a mixed-model ANOVA (and subsequent *t*-tests) was conducted to determine the effects of the independent variables on range during the visual distraction segment of the flight. Third, a principal components analysis (PCA) was conducted to determine what, if any, linear combinations of tactor positions existed (strategy by pilot to use tactor information) with respect to the stimulus intensity data recorded per observation (observations were sampled every 100 ms of flight). This was an exploratory analysis given that prior data and theory regarding use of the tactors in this scenario does not exist. A varimax rotation was applied to maximize the variance and to ease interpretation. Note that PCA is a multivariate statistical method used primarily for data reduction (see Johnson & Wichern [2007] for more detailed information). Scores on the linear combinations were then entered as predictors into a linear regression model with range as the outcome variable. It should be noted that the sample size for the PCA was 64 which is acceptable. However, a larger sample size is optimal for this kind of analysis since it takes a large sample for correlations to stabilize and the analysis is based on the correlation matrix. Despite a relatively small sample size, the analysis was conducted given that the ratio of cases to variables exceeded 5:1 (actual ratio was 8:1) and the correlations between the variables (tactors) exceeded 0.30.

Results

The primary objective of this study was to assess the efficacy of tactile cues, delivered by means of TSAS-Lite, a belt, for target orientation in helicopter extractions over moving targets. The primary outcome measure of performance, referred to as target range, was recorded in feet.

Mood and alertness assessments

The POMS data were analyzed using a repeated measures MANOVA that showed a significant main effect of *state* (rested, fatigued) on the following factors: tension-anxiety, vigor-activity, fatigue-inertia, and confusion-bewilderment (figure 5). Specifically, scores on tension-anxiety, fatigue-inertia, and confusion-bewilderment factors increased when fatigued versus rested while scores on vigor-activity decreased. Responses on the VAS were also analyzed using a repeated measures MANOVA that showed a significant main effect of *state* (rested, fatigued) on the following state adjectives: alertness, energetic, confident, irritable, sleepy, and talkative, (figure 6). The results show that participants rated themselves as less alert, energetic, confident, and talkative when fatigued versus rested. Alternatively, participants rated their mood as more irritable and sleepy when fatigued compared to when rested. Finally, PVT data were analyzed using paired samples *t*-tests which showed significantly slower reaction times, $t(15) = -3.408$, $p = 0.004$, and significantly more lapses, $t(15) = -5.074$, $p < 0.001$, when fatigued versus rested (figure 7). Results for the POMS and VAS are included in table 2.

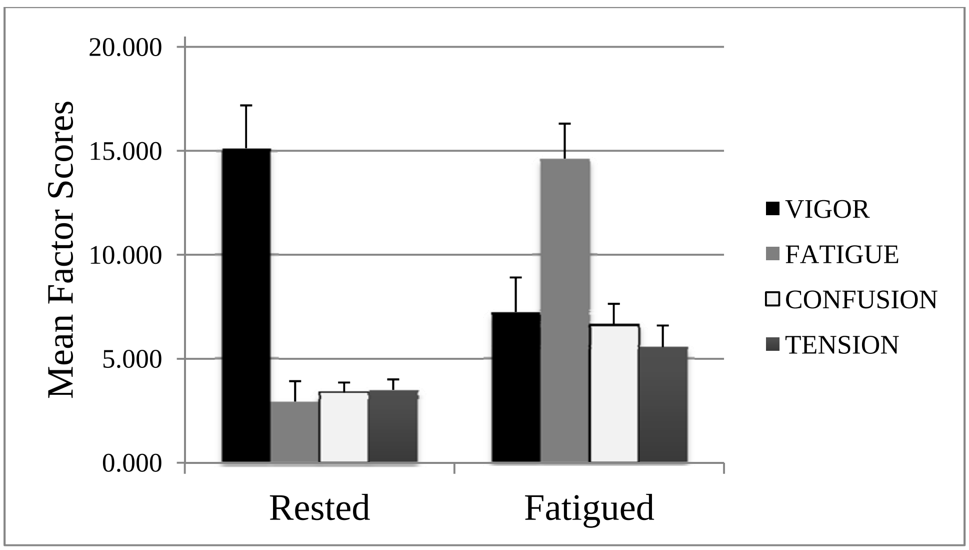

Figure 5. Main effect of *state* on POMS factors. Error bars represent standard error of the mean.

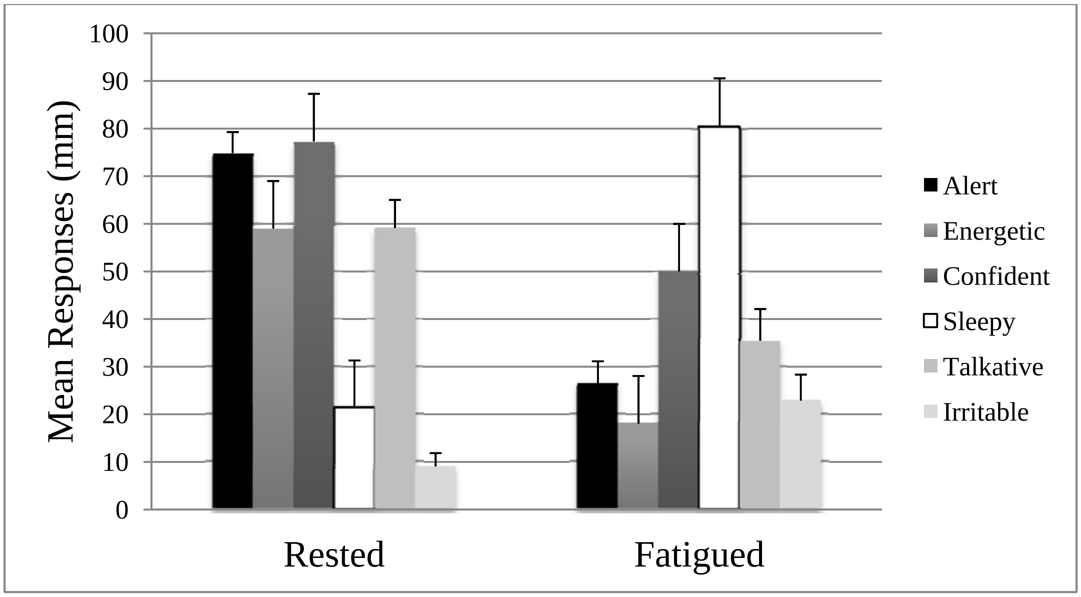

Figure 6. Main effect of *state* on VAS responses. Error bars represent standard error of the mean.

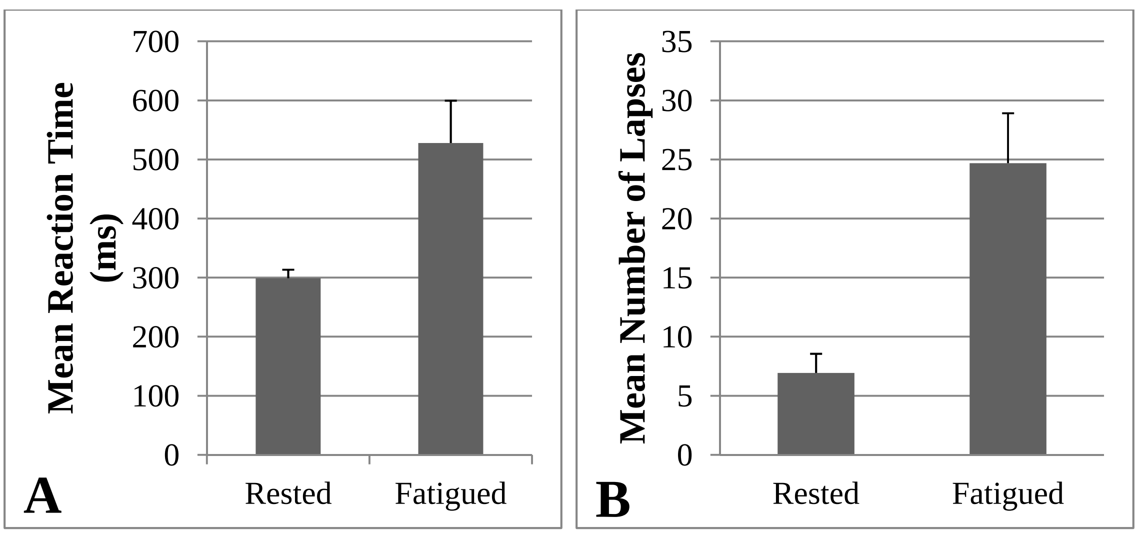

Figure 7. Effect of *state* on PVT outcomes: (a) mean reaction time and (b) mean number of lapses. Error bars represent standard error of the mean.

Table 2.

Summary of results of repeated measures MANOVAs for POMS and VAS data.

Factor/ Adjective	***F***	**df**	***p***	***Partial η^2***	***M***	***SE***
Effect of state (rested [r], fatigued [f])						
POMS						
Tension/Anxiety	4.886	1, 15	0.043	0.246	3.500 (r)	0.51 (r)
					5.563 (f)	1.04(f)
Depression/ Dejection	3.583	1, 15	0.078	0.193	0.625 (r)	0.34 (r)
					2.688 (f)	1.03 (f)
Anger/Hostility	3.989	1, 15	0.064	0.210	0.500 (r)	0.30 (r)
					1.875 (f)	0.72(f)
Vigor/Activity	37.420	1, 15	< 0.001	0.714	15.125 (r)	2.06 (r)
					7.250 (f)	1.66 (f)
Fatigue/Inertia	47.968	1, 15	< 0.001	0.762	2.938 (r)	0.99 (r)
					14.625 (f)	1.68 (f)
Confusion/ Bewilderment	9.566	1, 15	0.007	0.389	3.375 (r)	0.48 (r)
					6.625 (f)	1.02 (f)
VAS						
Alert	92.530	1, 15	< 0.001	0.861	74.875 (r)	4.41 (r)
					26.500 (f)	4.65 (f)
Anxious	3.826	1, 15	0.069	0.203	11.188 (r)	3.97(r)
					20.875 (f)	5.23(f)
Energetic	69.599	1, 15	< 0.001	0.823	59.000 (r)	5.49 (r)
					18.063 (f)	4.98 (f)
Confident	17.299	1, 15	0.001	0.536	77.313 (r)	4.65 (r)
					50.000 (f)	7.52 (f)
Irritable	6.522	1, 15	0.022	0.303	9.063 (r)	2.81 (r)
					22.88 (f)	5.47 (f)
Nervous	2.936	1, 15	0.107	0.164	8.188(r)	2.56 (r)
					18.625 (f)	5.53 (f)
Sleepy	83.378	1, 15	< 0.001	0.848	21.313 (r)	5.23 (r)
					80.563 (f)	4.53 (f)
Talkative	16.419	1, 15	0.001	0.523	59.125 (r)	5.92 (r)
					35.438 (f)	6.69 (f)

Post-flight and situational awareness questionnaires

Responses on the post-flight questionnaire were analyzed using a repeated-measures MANOVA that showed a significant main effect of *state* on cognitive workload, such that, when fatigued, participants rated their workload to be higher than when rested (figure 8.A). There was a significant main effect of *TSAS-Lite belt* such that participants rated their perception of target drift relative to their position as better when TSAS was active versus inactive, and they rated their SA as better when TSAS was active versus inactive (figure 8.B). There was a significant main effect of *visual environment* (figure 9), which showed that perception of target position and SA were rated as worse when the *visual environment* was degraded than when it was clear. Alternatively, participants rated mental stress of the flight physical workload and cognitive workload as greater when the *visual environment* was degraded versus clear. No interaction terms were significant. Note that one participant was excluded from the post-flight questionnaire analysis due to missing data for one condition. The analysis of the CLSA data (repeated-measures ANOVA) revealed a main effect of *TSAS-Lite belt* such that when the belt was active participants rated SA as greater than when the belt was inactive (figure 10). Results of the analysis of the post-flight questionnaire (limited to main effects given the lack of significant interactions) and CLSA are included in tables 3 and 4.

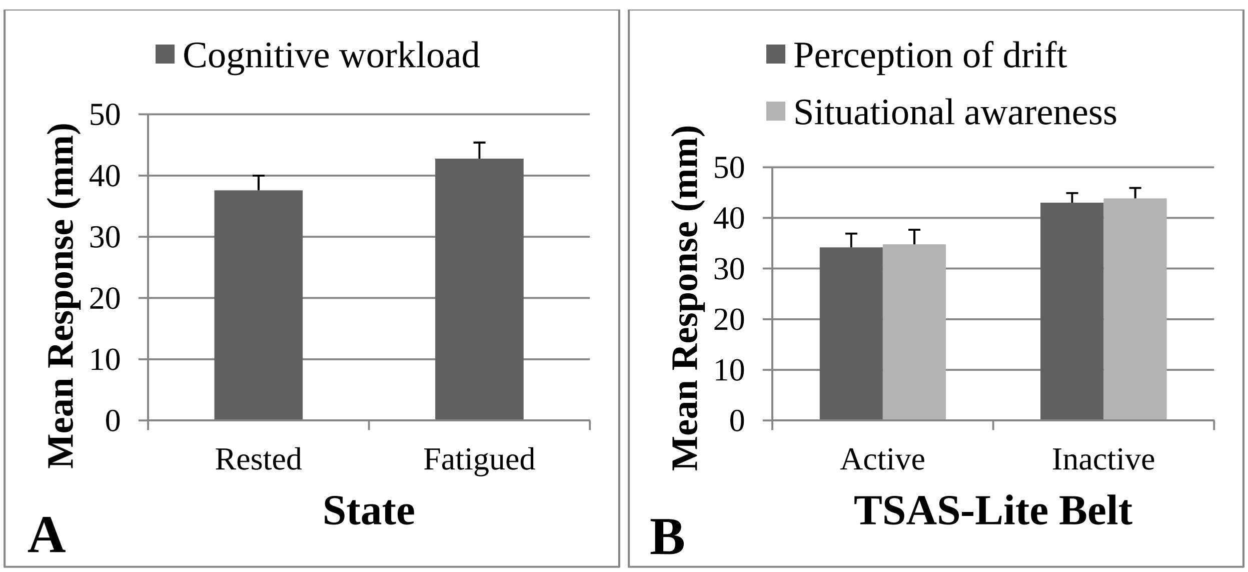

Figure 8. Main effect of (a) *state* and (b) *TSAS-Lite belt* on post-flight questionnaire responses. Error bars represent standard error of the mean.

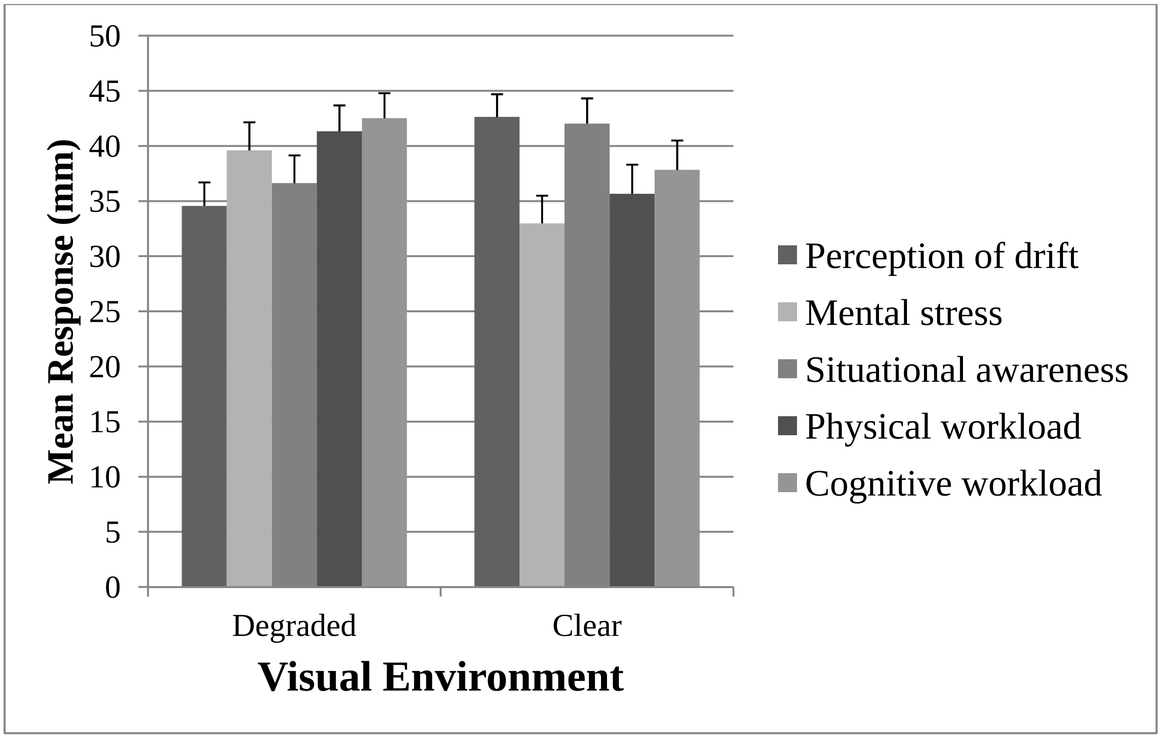

Figure 9. Main effect of *visual environment* on post-flight questionnaire responses. Error bars represent standard error of the mean.

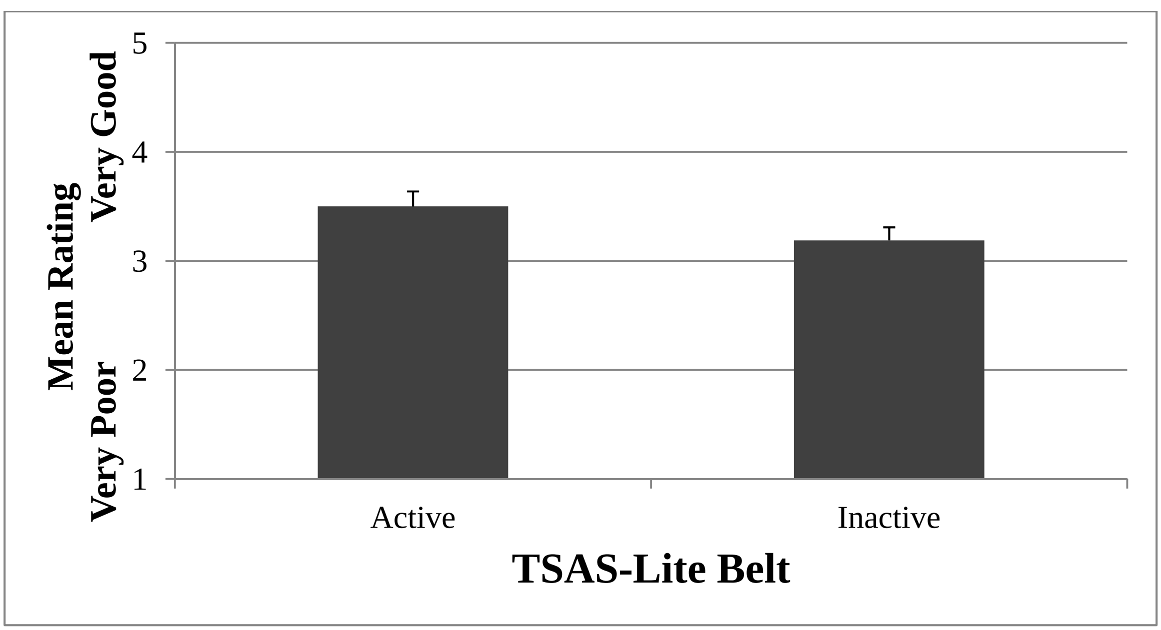

Figure 10. Interaction of *state* and *TSAS-Lite belt* on rating of situational awareness (CLSA). Error bars represent standard error of the mean.

Table 3.
Summary of results of repeated measures MANOVA for post-flight questionnaire data.

Factor/Adjective	***F***	**df**	***p***	***Partial η²***	***M***	***SE***
			Main effect of state (rested [r], fatigued [f])			
Perception of drift	0.849	1, 14	0.373	0.057	39.43 (r)	1.59 (r)
					37.76 (f)	2.45(f)
Mental stress	1.274	1, 14	0.278	0.083	34.56 (r)	2.41 (r)
					38.02 (f)	3.07 (f)
Situational awareness	4.068	1, 14	0.063	0.225	41.40 (r)	2.09 (r)
					37.27 (f)	2.82(f)
Visual workload	1.834	1, 14	0.197	0.116	39.58 (r)	2.21 (r)
					42.25 (f)	2.61 (f)
Physical workload	1.762	1, 14	0.206	0.112	36.80 (r)	2.77 (r)
					40.20 (f)	2.53 (f)
Cognitive workload	5.339	1, 14	0.037	0.276	37.58 (r)	2.41 (r)
					42.76 (f)	2.62 (f)
			Main effect of TSAS-Lite belt (active [a], inactive [i])			
Perception of drift	9.423	1, 14	0.008	0.402	34.18 (i)	2.73 (i)
					43.02 (a)	1.89 (a)
Mental stress	0.152	1, 14	0.702	0.011	36.57 (i)	2.56 (i)
					36.01 (a)	2.22 (a)
Situational awareness	18.410	1, 14	0.001	0.568	34.80 (i)	2.87 (i)
					43.87 (a)	2.05(a)
Visual workload	1.291	1, 14	0.275	0.084	42.33 (i)	2.56 (i)
					39.50 (a)	2.51 (a)
Physical workload	0.298	1, 14	0.593	0.021	38.03 (i)	2.51 (i)
					38.97 (a)	2.44 (a)
Cognitive workload	1.172	1, 14	0.297	0.077	38.85 (i)	2.79 (i)
					41.50 (a)	2.32 (a)
			Main effect of visual environment (degraded [d], good [g])			
Perception of drift	17.201	1, 14	0.001	0.551	34.56 (d)	2.13 (d)
					42.63 (g)	2.06 (g)
Mental stress	9.763	1, 14	0.007	0.411	39.60 (d)	2.55 (d)
					32.98 (g)	2.51 (g)
Situational awareness	11.017	1, 14	0.005	0.440	36.63 (d)	2.51 (d)
					42.03 (g)	2.29 (g)
Visual workload	4.483	1, 14	0.053	0.243	43.63 (d)	2.23 (d)
					38.20 (g)	2.84 (g)
Physical workload	9.430	1, 14	0.008	0.402	41.33 (d)	2.35 (d)
					35.67(g)	2.64 (g)
Cognitive workload	5.143	1, 14	0.040	0.269	42.52 (d)	2.27 (d)
					37.83 (g)	2.67 (g)

Table 4.
Summary of results of repeated measures ANOVA for CLSA data.

	F	**df**	***p***	***Partial η^2***	***M***	***SE***
Main effect: State	2.778	1, 15	0.116	0.156	3.500 (r)	0.13 (r)
(rested [r], fatigued [f])					3.188 (f)	0.16(f)
Main effect: TSAS-Lite belt	6.818	1, 15	0.020	0.313	3.500 (a)	0.14 (a)
(active [a], inactive [i])					3.188 (i)	0.12 (i)
Interaction:						
TSAS-Lite belt, state	3.462	1, 15	0.083	0.188		

Hover maneuver over moving target

To assess the efficacy of the *TSAS-Lite belt* during hover over a moving target, a 2^4 mixed-model was tested. Three within-subject factors were entered into the model: *visual environment* (degraded, clear), *state* (rested, fatigued), and *TSAS-Lite belt* (active, inactive). An additional between-subjects factor was added to the model: *training amount* (minimal, additional). The visual inspection and analysis of standardized residuals did not indicate any influential observations or violations of assumptions. The results of the factorial yielded significant main effects of *visual environment* and *TSAS-Lite belt*. There were no significant interactions. Specifically, participants were able to stay closer to the target when the *visual environment* was clear versus degraded. Finally, the main effect of *TSAS-Lite belt* showed that participants' performance was better (closer to the target) when *TSAS-Lite belt* was active versus inactive. Figure 11 below illustrates the main effects. Note that one participant was excluded from the analysis due to missing data for one condition. Results are included in table 5.

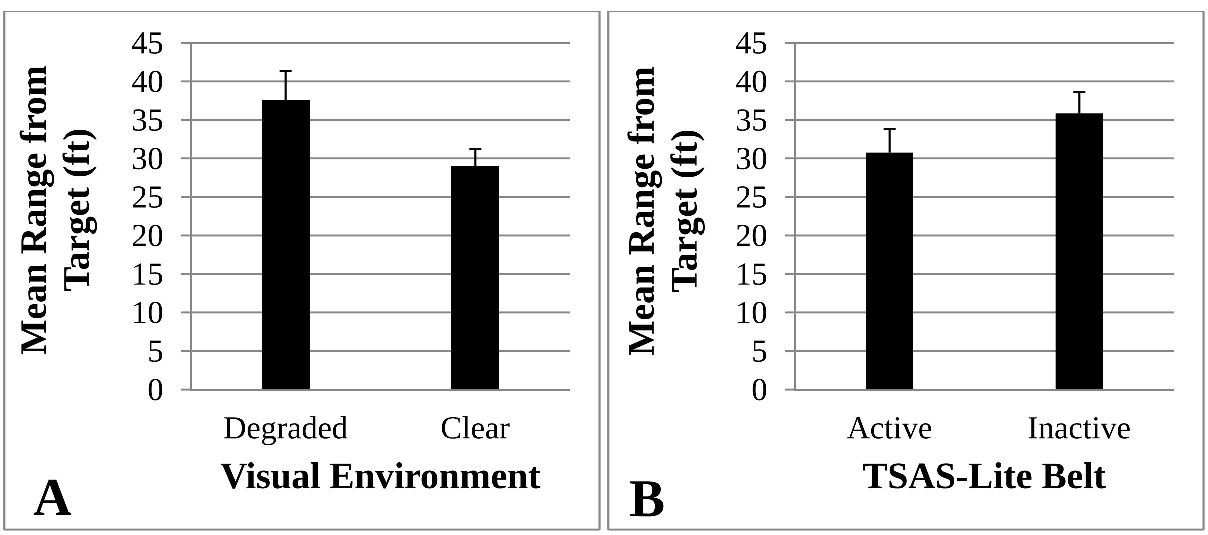

Figure 11. Main effects of (a) *visual environment* and (b) *TSAS-Lite belt* on mean range from target (ft). Error bars represent standard error of the mean.

Table 5.
Summary of results of 2^4 mixed-model ANOVA: Hover maneuver over moving target.

	F	df	*p*	*Partial* η^2	*M*	*SE*
Main effect: State (rested [r], fatigued [f])	0.233	1, 13	0.638	0.018	33.038 (r) 34.432 (f)	3.36 (r) 3.04 (f)
Main effect: TSAS-Lite belt (active [a], inactive [i])	7.684	1, 13	0.016	0.371	31.144 (a) 36.326 (i)	3.17 (a) 2.84 (i)
Main effect: Visual (degraded [d], good [g])	9.750	1, 13	0.008	0.429	37.802 (d) 29.668 (g)	3.82 (d) 2.28 (g)
Main effect: Training (minimal [m], additional [a])	1.603	1, 13	0.228	0.110	37.356 (m) 30.114 (a)	3.91 (m) 4.18 (a)
Interaction: Visual*Training	2.023	1, 13	0.179	0.135		
Interaction: TSAS*Training	0.001	1, 13	0.970	0.001		
Interaction: Visual*State	1.011	1, 13	0.333	0.072		
Interaction: Visual*TSAS	0.238	1, 13	0.634	0.018		
Interaction: State*TSAS	0.765	1, 13	0.398	0.056		
Interaction: State*Training	0.581	1, 13	0.460	0.043		
Interaction: Visual*State*TSAS	0.052	1, 13	0.823	0.004		
Interaction: Visual*State*Training	0.323	1, 13	0.580	0.024		
Interaction: Visual*TSAS*Training	0.001	1, 13	0.983	0.001		
Interaction: State*TSAS*Training	0.165	1, 13	0.691	0.013		
Interaction: State*TSAS*Training* Visual	0.343	1, 13	0.568	0.026		

Visual distraction: Hover maneuver over moving target

To assess the efficacy of the TSAS-Lite system during hover over a moving target while visually distracted, a 2^4 mixed- factorial model was built and tested. Three within-subject factors were entered into the model: *visual environment* (degraded, clear), *state* (rested, fatigued), and *TSAS-Lite belt* (active, inactive). An additional between-subjects factor was added to the model: *training amount* (minimal, additional). The visual inspection and analysis of standardized residuals did not indicate any influential observations or violations of assumptions. The results of the factorial yielded non-significant results (table 6). Note that six participants were excluded from the analysis due to missing data for at least one condition.

Table 6.
Summary of results of 2^4 mixed-model ANOVA: Visual distraction – hover maneuver over moving target.

	F	df	*p*	*Partial η^2*	*M*	*SE*
Main effect: State (rested [r], fatigued [f])	0.075	1, 8	0.791	0.009	44.185 (r) 45.987 (f)	3.78 (r) 4.97 (f)
Main effect: TSAS-Lite (active [a], inactive [i])	2.551	1, 8	0.149	0.242	42.217 (a) 47.955 (i)	3.08 (a) 3.80 (i)
Main effect: Visual (degraded [d], good [g])	0.017	1, 8	0.901	0.002	45.315 (d) 44.857 (g)	2.62 (d) 4.12 (g)
Main effect: Training (minimal [m], additional [a])	2.379	1, 8	0.162	0.229	49.641 (m) 40.531 (a)	4.18 (m) 4.18 (a)
Interaction: Visual*Training	0.001	1, 8	0.976	0.001		
Interaction: TSAS*Training	3.249	1, 8	0.109	0.289		
Interaction: Visual*State	0.146	1, 8	0.712	0.018		
Interaction: Visual*TSAS	2.602	1, 8	0.145	0.245		
Interaction: State*TSAS	0.000	1, 8	1.000	0.000		
Interaction: State*Training	1.121	1, 8	0.321	0.123		
Interaction: Visual*State*TSAS	0.248	1, 8	0.632	0.030		
Interaction: Visual*State*Training	0.004	1, 8	0.952	0.001		
Interaction: Visual*TSAS*Training	1.838	1, 8	0.212	0.187		
Interaction: TSAS*State*Training	0.123	1, 8	0.735	0.015		
Interaction: State*TSAS*Training* Visual	0.281	1, 8	0.610	0.034		

Tactors

The total number of tactile stimuli dispatched was calculated and subsequently used to calculate the proportions of cues by each tactor (labeled with respect to location) per flight. The mean proportions of total stimuli transmitted by each tactor were then calculated (figure 12). The greatest proportion of stimuli was fired from the back tactor at the intensity level of 2 (moderate stimulus [figure 13]).

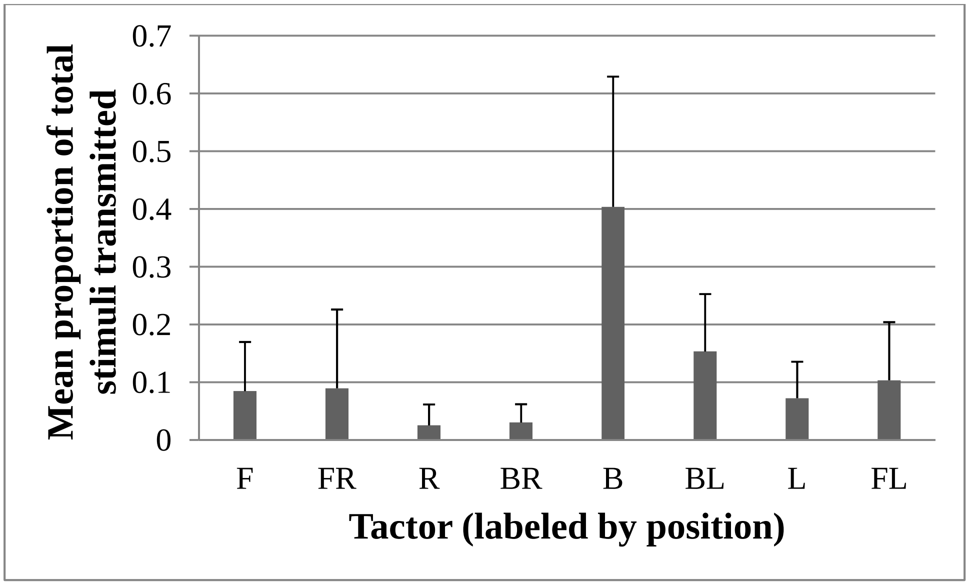

Figure 12. Mean proportion of total stimuli transmitted by each tactor (labeled with respect to position). Error bars represent standard deviation.

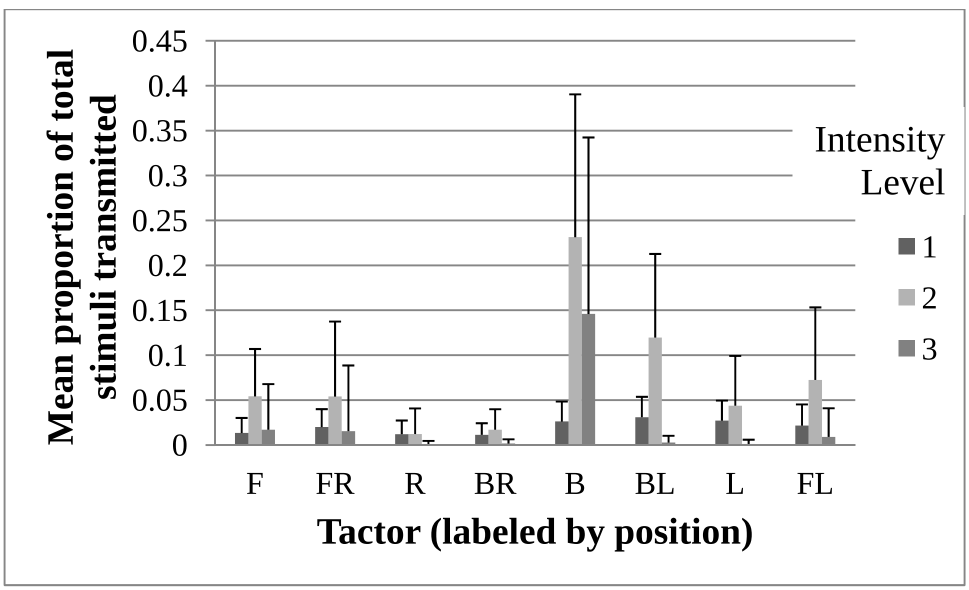

Figure 13. Mean proportion of total stimuli transmitted by each tactor (labeled with respect to position) at each stimulus intensity level. Error bars represent standard deviation.

Principal components analysis (correlation matrix) was used to identify and compute composite tactor scores, or rather the linear combinations of tactors depicting a task strategy. The initial eigenvalues showed that the first component explained 34.27 percent of the variance, the

second 27.61 percent of the variance, and the third 13.15 percent of the variance. The remaining components had eigenvalues below one, each factor explaining 10 percent or less of the data. A scree plot showed a "leveling off" after three factors. The initial eigenvalues and scree plot taken together supported the inclusion of the first three components in the final solution. Table 7 presents the loadings of each tactor on the unrotated components. Items with component loadings of 0.50 or greater were identified as contributing to a particular factor. From inspection of the principal-component loadings, it appears that the first component is a contrast of the back tactor (B) to the left tactors (FL, L). The second component appears to be a combination of the right tactors (R, BR). The third component is a contrast of the front tactors (FR, F) to the back-left tactor (BL). These scores as well as *visual environment* (degraded, clear) and *state* (rested, fatigued) conditions were then entered in a multiple linear regression model as predictors. Mean range from target was entered as the outcome variable. Inspection of the residuals suggests that the model assumptions were not violated. The model was significant ($F(5, 58) = 6.348$, $p > 0.001$) explaining 35.4 percent of the variance ($R^2 = 0.354$). Scores on principal components 1 and 2 were significant predictors of mean range from target, $\beta = -6.433$, $t = -3.634$, $p = 0.001$ and $\beta = -5.094$, $t = -2.966$, $p = 0.004$, respectively. The predictor *visual environment* approached significance, $\beta = -6.317$, $t = -1.801$, $p = 0.077$.

Table 7.
Tactors and rotated principal-components loadings.

	Components		
Tactors	1	2	3
FL	0.856	-0.235	0.007
F	0.401	-0.183	0.734
FR	-0.024	0.390	0.692
R	0.048	0.898	0.214
BR	-0.280	0.828	0.081
B	-0.809	-0.225	-0.317
BL	0.212	-0.237	-0.715
L	0.810	-0.180	-0.395

Note. Each tactor was labeled by location: front left (FL), front (F), front right (FR), back right (BR), back (B), and left back (LB).

Discussion

The primary objective of this study was to evaluate the efficacy of a tactile system providing directional cues to maintain and/or improve pilot performance during a hover maneuver over a dynamic target. The findings support the tactile system as an effective device for facilitating performance of this task under varied conditions (rested versus fatigued, degraded versus clear visual environment). Additionally, the data patterns indicate that participants developed a strategy for using the cues (in some cases with minimal training) which influenced performance.

Fatigue

Changes in mood and alertness were evident in the results. Specifically, participants' alertness, vigor, energy, confidence, and talkativeness decreased after one night of sleep deprivation whereas sleepiness, irritability, confusion, and fatigue increased. Performance on the psychomotor vigilance task also decreased on Day 2 of the data collection. In conjunction, these findings suggest that participants were, in fact, affected by the fatigue on Day 2.

Flight performance (range from target) in this study was not affected by fatigue despite participants exhibiting evidence of fatigue. One explanation for this discrepancy is that the psychomotor vigilance task (a simple and monotonous task) did not engage the participants sufficiently to put forth the effort to overcome sleepiness while the more arousing task of the flight simulator did engage the participants. Previous research on effects of sleep deprivation has shown that more basic tasks including reaction time and vigilance tasks show deficits under conditions of sleep deprivation. However, these deficits do not necessarily transfer to more complex tasks. It has been argued that high level complex tasks are relatively unaffected due to the arousal they generate and the need for energy to be expended to overcome any fatigue or sleepiness. Harrison and Horne (2000) critically examined this assumption and indicated that while this may be true for some tasks, there are tasks involving complex skills that rely heavily on prefrontal cortex function. Research has shown that this region of the brain is particularly impacted after as little as one night of sleep deprivation (e.g., Horne, 2000). According to this review, tasks that seem to be unaffected are complex, logical, interesting, and rule-based. Tasks that are uninteresting, monotonous, too simple, or too long in duration are affected.

Pilot strategy

Inspection of the data for each individual tactor showed that some participants developed a strategy of using the tactors to reduce the risk of the rotor blades striking the two shipboard antennae located in front of the aircraft on both the left and right side. Although the participants were instructed to maintain a hover over the center of the deck, some participants determined they could avoid collision with the antennae while remaining slightly behind the center of the deck position simply by deliberately maintaining a contact with the tactor cues at a moderate stimulus intensity on the back, back left and back right tactors. Such participants could more easily maintain a safe buffer distance between the rotor blades and the forward antennae.

An exploratory analysis of the linear combinations of tactors revealed two 'strategies' that enhanced performance. The first strategy is a contrast of back and left tactors (specifically, contrast of the back tactor to a combination of the tactors at the left and front left positions). The second strategy is a combination of the back right and right tactors. Both strategies employ the back tactors further supporting the observation above.

Training

The first exposure to novel instruments increases the cognitive workload of pilots. In a prior in-flight experiment with TSAS (Schultz, McGrath, Cheung, & Rupert, 2009), training was provided to rested pilots in the days prior to the flight. The current experiment did not afford the

opportunity for training of pilots in the days preceding the experiment. The additional training was provided to pilots under conditions of ever increasing fatigue which may explain why no significant performance effect was seen in the group with additional training periods.

Hover Performance

Schultz et al. (2009) demonstrated a performance improvement of 59 percent in horizontal positioning accuracy when TSAS was available during a high hover maneuver in a degraded visual environment. While the current experiment demonstrated improved performance when the TSAS-Lite belt was active, the results did not support an interaction of the *TSAS-Lite belt* with the *visual environment*. The most probable explanation is that the presence of the ship's antennae in the foreground provided a strong visual orienting cue in both the good and degraded visual conditions. Even when the visibility was reduced to a quarter mile and the horizon was poorly defined, the two antennae were clearly visible. Recent simulator studies (Chesapeake Technology International, 2011) using a continuously degrading visual environment demonstrated that pilots could maintain a safe hover using TSAS when the degraded visual environment reached 97 percent but they could not perform this maneuver in the absence of TSAS. Future studies should involve performance when the degraded visual environment attains total obscuration which is frequently reported as the environmental condition in Army class A (defined as fatality, destruction of aircraft, or property damage equal to or exceeding $2,000,000) helicopter mishap reports.

Future Research

While the results of this study provide important contributions supporting the tactile system studied, much work is yet to be done. Three recommendations for future research are made:

a. Perform in-flight degraded visual environment tests while recording pilot gaze and pilot inputs to controls to objectively demonstrate that the TSAS-Lite belt reduces pilot workload and improves performance under conditions currently experienced in-theater.

b. Conduct experiments to demonstrate the role of the TSAS-Lite belt in reducing pilot fatigue during long duration flights.

c. Determine the optimal amount of TSAS-Lite belt training time to most effectively prepare pilots to use TSAS.

Army requirements and future direction

The Department of Defense and Program Executive Office (PEO) Aviation have given high priority to solving the problem of safe operation in degraded visual environments. The three pronged approach involves: 1) development of improved flight control algorithms; 2) new sensors that can penetrate obscurations; and 3) improved cueing technologies to include tactile cueing. As a result of demonstrations of the TSAS technology to Army aviation requirements personnel, several acquisition documents have been developed (Functional Needs Analysis, Functional Solutions Analysis, and Initial Capabilities Document) resulting in a requirement to include tactile cueing in the Aircraft Survivability requirements document signed in 2011.

Additionally the Air Warrior program under PEO Soldier has included tactile cueing in the Capability Development Document (CDD) for Air Soldier System which was also signed in 2011. In support of TSAS implementation in Army aviation cockpits, continued evaluation of the effectiveness of the system to maintain and enhance performance under varied conditions and operating in concert with the new sensors and flight control algorithms are recommended. More specifically, research to determine the optimal amount of training is needed. In addition to continued research, it is essential that demonstrations of TSAS are provided to key decision makers involved in the acquisition system to place TSAS on military aviation platforms.

Conclusions

The results of this study support the efficacy of directional cues provided by a tactile system for maintaining/improving pilot performance during a hover maneuver over dynamic targets. Specifically, pilots were able to safely maintain a closer position over the target when TSAS-Lite was active. Also, pilots perceived workload to be diminished when the tactile system was active thus indicating that the additional information was not a burden or distraction to the pilot.

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